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# Designing for Maintainability and System Availability

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## DESIGNING FOR MAINTAINABILITY AND SYSTEM AVAILABILITY

### 1. INTRODUCTION

The final goal for a delivered system (whether a car, aircraft, avionics box or computer) should be its availability to operate and perform its intended function over its expected design life. Hence, in designing a system, we cannot think in terms of delivering the system and just walking away. The system supplier needs to provide support throughout the operating life of the product. This involves a number of concepts as shown in Fig.1--System Supportability Requirements. Here, supportability requires an effective combination of reliability, maintainability, logistics and operations engineering (as well as safety engineering) to have a system that is available for its intended use throughout its designated mission lifetime (see Fig.3--Definitions, for more details). Maintainability is a key driving element in the effective support and upkeep of the system as well as providing the ability to modify and up-grade the system throughout its lifetime.

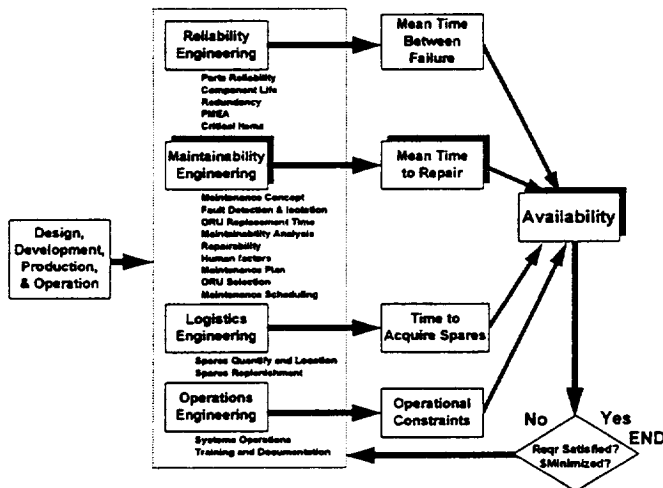


Fig.1--System Supportability Requirements

This paper then, will concentrate on maintainability and its integration into the system engineering and design process. The topics to be covered (as Fig.2 shows) include elements of maintainability, the total cost of ownership, how system availability, maintenance and logistics costs and spare parts

### Fig.2--MAINTAINABILITY TOPICS

- Elements of Maintainability
- Total Cost of Ownership.
- Maintainability and System Analysis.
- Maintainability Processes and Documents.
- Maintainability Analysis Mathematics.
- Additional Considerations
- Maintainability Problems.
- Conclusions.

cost effect the overall program costs. System analysis and maintainability will show how maintainability fits into the overall systems approach to project development. Maintainability processes and documents will focus on how maintainability is to be performed and what documents are typically

generated for a large scale program. Maintainability analysis shows how tradeoffs can be performed for various alternative components. The conclusions summarize the paper and are followed by specific problems for hands-on training.

Fig.3--DEFINITIONS<sup>1</sup>

- **RELIABILITY:** The probability that an item can perform its intended functions for a specific interval under stated conditions.
- **AVAILABILITY:** A measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown (random) point in time. (2) The probability of a system readiness over a long interval of time.
- **MAINTAINABILITY:** (1) A system effectiveness concept that measures the ease and rapidity with which a system or equipment is restored to operational status after failing. (2) A probability that a failed system can be restored to operating condition in a specified interval of downtime
- **SAFETY (Analysis):** Analysis that considers the possible types, reasons, and effects of operation and failures on the system that will affect the personal safety of persons that operate or maintain a device.
- **LOGISTICS:** The art and science of the management, engineering, and technical activities concerned with requirements, design, and planning and maintaining resources to support objectives, plans, and operations.
- **OPERATIONS:** The defining of the environment, schedule, loading, input and output parameters in which a system is to function and the tasks the system is to perform.

The importance of maintainability is further noted in Fig.4 and Fig.5. All too often, the performance specifications or the appearance of a product are the overriding factors in its acquisition or purchase. This attitude of course, can be extremely detrimental when the first failure occurs. Availability of critical parts and ease of maintenance keep critical systems operating.

Finally please note that the majority of the mathematical analysis and examples will concentrate on the maintainability analysis at the component level or below. In a highly com-

<sup>1</sup> Some more basic definitions are as follows:

**Reliability:** What is the chance of a failure that will stop the system from operating. This is usually a random, "unexpected" failure rather than wearout of brakes, a clutch or a fatigue failure which can be predicted (when a given input load spectrum is known).

**Availability:** the probability of the system being ready to operate when needed; can be met by having very high reliability or very small maintenance requirements (easy maintainability along with a good supply of spare parts) or a combination of both. As an example what was the percentage of times a car started out of the total number of tries over its lifetime. Alternatively, how many days was it in your driveway ready to start (as oppose to being in the garage for repairs).

**Maintainability** can be thought of as how easy it is to diagnose the problems in a failed (or marginally operable) system and how easy it is to replace the failed components (or software) after this diagnosis has been made. If a system is not reliable and prone to partial or complete failures and if it is difficult to find out what is causing a system to malfunction and it is difficult to "get to" and replace failed components, then we have a serious problem that needs to be corrected.

plex and redundant system the evaluation of availability at a system level may be extremely difficult and is beyond the scope of this paper. Redundancy, switches and software which can be used to bypass failed subsystems and other methodologies can allow a system to operate even with some system degradation. The treatment of these types of problems is beyond the scope of this paper.

Fig.4--IMPORTANCE OF MAINTAINABILITY

- A large integrated system can come from the best possible design, utilizing the newest technology. It can be a work of art and outperform any competitive system. But who would want it?
- If system breakdowns cannot be diagnosed to a level of detail needed to pinpoint the problem in a short time,
- If spare parts are not readily available,
- If repair requires extremely long lead times,
- If installing the spare parts is extremely difficult,
- If checkout and or alignment of spare parts is difficult,
- Then the system is not available (operational) for all practical purposes!



Fig.5--Parts Are Needed

## 2. ELEMENTS OF MAINTAINABILITY

We need to consider up-front in our design the things that must be done to maintain the system. Either the system will not fail for the entire mission or whatever parts of the system fail need to be replaced. If we do not have a system with perfect reliability and no wearout, the following questions (as illustrated by Fig.6 need to be asked:

*What parts have high failure rates and how will their failure be diagnosed?* Example: if a Cathode Ray Tube (CRT) screen does not show a display has the screen failed, or has a power supply failed or has a computer stopped sending the screen data?

*Can various problems be diagnosed easily?* How quickly can the problem be diagnosed. If there is an intermittent fault can information during this anomaly be retrieved later? If a failure can not be isolated or insufficient diagnostic capabilities built into the system restoration of the system can be a time consuming task.

*How quickly can the system be repaired?* Has the system been segmented into easily replaceable units? Are parts buried on top of one-another with hundred of attachment points between units? Also can software be used to detect

and route around a hardware failure and make the failure transparent to the user.

*Where will spare parts be stored?* How many spare units should be ordered? Will parts for a unit in Washington be lost in a warehouse in Los Angeles? Will there be an over-supply of one unit and a shortage of another?

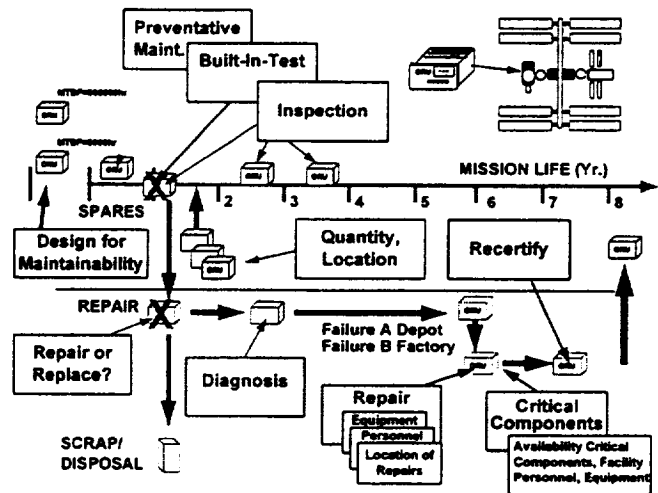


Fig.6--Elements of Maintainability

*Will a failed unit be discarded or repaired?* If it is to be repaired, where should they be repaired? What equipment and personnel are required to do the work?

*Finally, will unique parts be available to repair the unit?* Will some unique part such as a traveling wave tube or low noise amplifier still be manufactured when they need to be replaced to repair a unit? Will the supplier who sold the unit repair them? If repairs are agreed to, will the supplier still be in business? (logistics issues)

All these questions need to be answered when planning a product. While some of these questions overlap with logistics (the science of supply and support of a system throughout its product life cycle), they all need to be considered. The maintenance concept to be used for the system and designing for maintainability both need to be first considered early in the design phase of the product. To do this, we need to first consider some definitions:

## 3. TOTAL COST OF OWNERSHIP

This total life cycle cost of a unit needs to be considered when evaluating the cost of a project. The need to support the system through an effective logistics program that includes consideration for maintainability is of paramount importance (see Fig.7 and Fig.8).

The project can follow a faster development course and procure less reliable hardware; however, the maintenance cost will make the project more expensive. Additionally, if the unit is not available because of lengthy maintenance processes or lack of spare parts, additional units must be procured to have the fleet strength at the desired level (whether it is delivery vehicles or a research aircraft).

Fig.7--TOTAL COST OF OWNERSHIP

- **Total Life Cycle Costs.** Not just the cost of flight units and a prototype unit.
- **Availability of the Unit.** Not just the neat things it does if it is running. Backup systems will be needed if the unit is down too often.
- **Maintenance and Logistics Costs.** Often these are 40% to 60% of total system costs.
- **Cost of Spares.** This is a function of reliability and speed with which the system can be maintained.

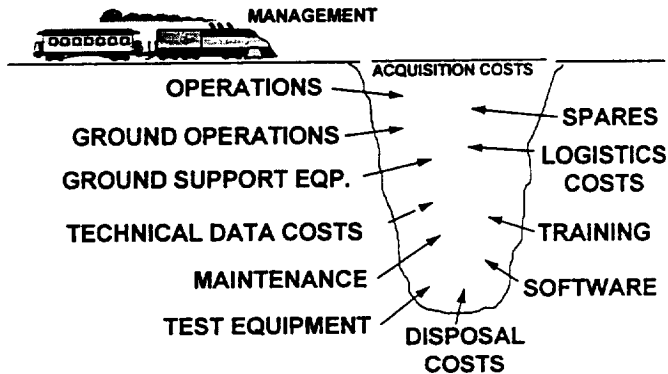


Fig.8--Hidden System Costs

Often all the costs associated with a project are not considered. Besides just the cost of producing the units, a huge amount of time and money must be expended keeping them operational throughout the mission lifetime. Some project costs are considered in Fig.9.

COST	DESCRIPTION
<b>Acquisition</b>	(1) Design & development: Research, trades, design, analysis, prototype production & test (2) Production.
<b>Operations</b>	Personnel, facilities, utilities, operating supplies and other consumables, maintenance ground OPS
<b>Ground operations</b>	Cost of ground support engineering model and test and checkout models, maintenance for these.
<b>GSE equipment.</b>	Cost of all test, checkout and diagnostic equipment, purchase, storage & calibration of GSE equipment.
<b>Technical data costs:</b>	Cost of all manuals, specifications, configuration management, SAV configuration management, data-base, storage.
<b>Training</b>	Continuing cost of training all operations & maintenance personnel.
<b>Maintenance</b>	(1) Cost of calibration and repair as well as system downtime. (2) Cost of repair facilities: cost of lab, depot or other repair facilities.
<b>Test equipment.</b>	Cost of equipment used for maintenance, alignment and recalibration of system as well as recertification for flight, etc.
<b>Software</b>	Cost of software maintenance and upgrades, test and installation.
<b>Logistics cost.</b>	Cost of packaging, storage, transportation and handling as well as support of tracking system, etc.
<b>Spares</b>	Actual cost of spare ORUs, LRUs as well as long-lead time items and other critical components.
<b>Disposal costs:</b>	Cost of disassembling, recycling, disposing of hazardous waste.

Fig.9--Description of Total Project Costs

Therefore total system costs must not only include design and development costs but a whole host of training, operations and maintenance costs as well (see Fig.10).

Fig.10 TOTAL SYSTEMS COST

- **Total system costs =**  
 design and development costs +  
 production costs +  
 operations costs +  
 technical data costs +  
 training costs +  
 maintenance costs +  
 test equipment costs +  
 software maintenance costs +  
 logistics and spares costs +  
 disposal costs

As quality and reliability of the system increases, classically the cost of the system increases as well but this may not necessarily be the case. As quality and reliability of the system are improved maintenance, logistics and spares cost decrease. Since total support costs are a function of maintenance costs and the total number of spares, spare repair and spare transport costs, improved reliability drastically reduces total cost of ownership as well.

#### 4. MAINTAINABILITY AND SYSTEM ENGINEERING

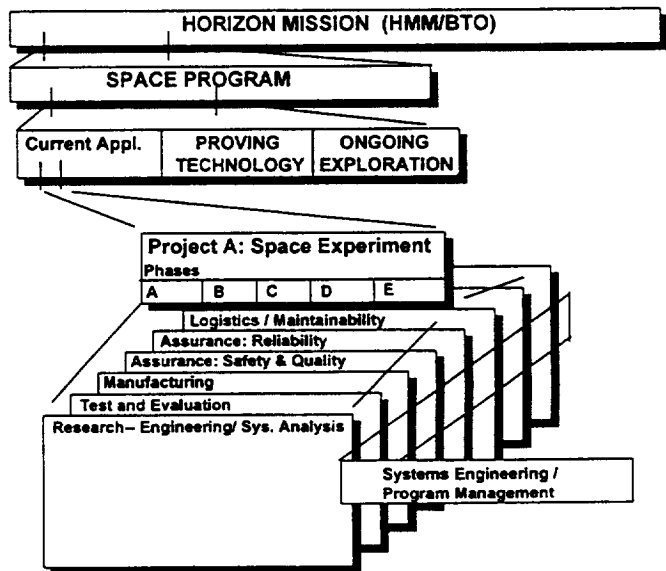


Fig.11--Systems Engineering and Maintainability

Fig.11 gives a global overview of a long-term research project such as the space program and how maintainability is a part of it. The Horizon Mission Methodology (HMM) was developed initially for the study of breakthrough-type space technology. HMMs are hypothetical space missions whose performance requirements cannot be met, even by extrapolating known space technologies. The missions serve to develop conceptual thinking and get away from simple projections and variations of existing capabilities.

Use of this with Breakthrough Technology Options (BTOs) has been developed to provide a systematic, analytical approach to evaluate and identify technological requirements for BTOs and to assess their potential for providing revolutionary capabilities for advanced space missions.

Therefore we can think of the space program (or other major research program) not just as a number of isolated projects but single unified program toward a global goal, e.g., the landing of men on the moon or a manned mission to Mars or establishing a permanent manned lunar base.

The program concept assumes a single consistent objective. It involves putting tested and proven equipment together to perform a step in the goal. Another area of work involves developing technology and components and ongoing exploration with the outer fringes of what you know lies ahead. Going to an individual project level, a number of different disciplines are brought together to design, develop, deploy and operate a given project. One of these disciplines as shown is maintainability. Expanding the various maintainability activities over project phases gives us the chart in Fig. 12. Systems engineering at the National Aeronautics and Space Administration (NASA) uses five phases to describe a mission. We strive to run our maintainability program across all five phases. The task descriptions are shown in the figure.

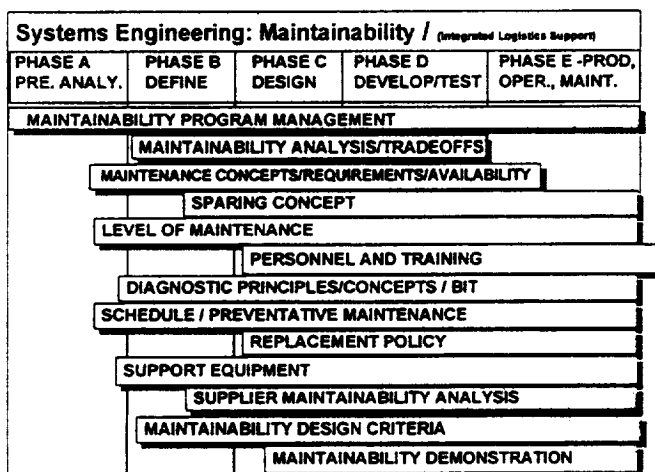


Fig. 12--Maintainability in the System Life Cycle

The various activities are defined in the following sections. The important thing is that the maintainability concept for the project be introduced early in the program. Without this, long term missions will see costs and downtime increase. True, initial development costs may increase, but total cost will be less. In some cases projects have ignored maintainability and built in diagnostics in order to get budgetary approval of a new system. But the final costs always increase because of this.

Finally Fig. 13 shows the interrelationship between the various tasks of the project and how work and information flows between operations, reliability and logistics functions. Basically, systems operation and mission requirements are evaluated to generate the maintainability concept. This con-

cept is further affected by component reliability and the various reliability analyses performed. This maintenance analysis then interacts with design engineering to develop a design that can be repaired and maintained.

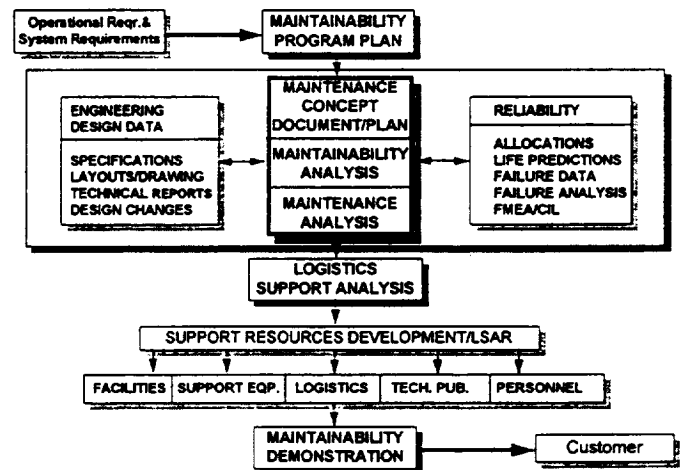


Fig. 13--Maintainability In the Systems Engineering Process

Finally, maintainability data and requirements flows to logistics to allow an effective support resource program to be developed. The output of the maintenance analysis is also critical to the logistics support analysis.<sup>2</sup> The Logistics Support Analysis Record (LSAR) and Support Resource development feed the plan for (1) facilities to house equipment or ground operations, (2) ground support equipment, (3) the logistics plan and other activities, (4) data (technical publication) for equipment operation and maintenance, and (5) identifying personnel and training needed to maintain, repair and support the equipment. Finally a maintainability demonstration is performed to evaluate the actual times needed to diagnose and physically change out a Line Replaceable Unit (LRU) or and Orbital Replaceable Unit (ORU).

## 5. MAINTAINABILITY PROCESSES and DOCUMENTS

The mission requirements analysis and the operational requirements of a new system are derived from the initial needs and wants of the community. Directly and simultaneously derived from this is the system maintenance concept (as described in the maintenance concept document).

Also an initial draft of maintenance requirements should be developed at this time. Operational requirements and system requirements are funneled into the Maintenance Concept Document. The maintenance concept document covers every aspect of a maintenance program throughout the life of the system as illustrated in Figure 14.

<sup>2</sup> The following general guideline is suggested to distinguish support, logistics and maintenance for this paper. Supportability encompasses all logistics, maintainability and sustaining engineering. Logistics is involved with all movement of ORUs and spare parts, the procuring and staging of spare parts, as well as developing storage containers, etc. Maintainability is responsible for (once the ORUs, etc. are located) the repair of ORUs, SRUs, PCBs, etc. which includes test and diagnostic equipment, tools and a suitable work area as well as training and providing maintenance personnel.

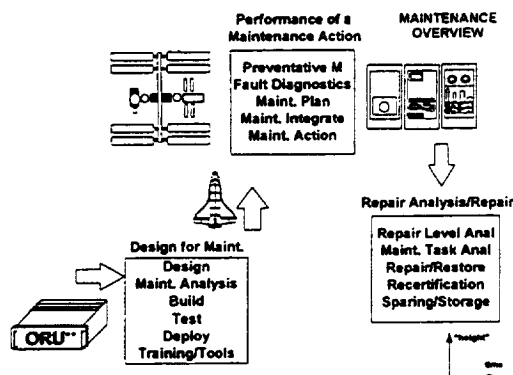


Fig. 14--Maintenance Activities

The *first phase* involves planning and designing for maintainability is made a part of the design process. This includes making components easy to service. In this first step, ORUs (Orbital Replaceable Unit) or LRUs (Line Replaceable Unit) are selected. As the name implies replaceable units can be quickly changed out to bring the system back into operation.

To speed the system back into operation, the system is typically divided into units that can easily be replaced on-orbit or on the flight line. A module or system is designated an ORU or an LRU if that part of the design has high modularity (it can be self contained such as a power supply) and low connectivity (there is a minimum of power and data cables to other parts of the system). As we will discuss later, we must be able to diagnose that an ORU or LRU has failed. This means that maintenance on-orbit (or on the flight line) will only replace these items. The system is built, tested, shipped and put into operation. Operations and maintenance training are also conducted.

The maintainability analysis (see Fig. 15) also uses (1) predicted times for corrective maintenance x number of failures, (2) predicted times preventive maintenance x the number of scheduled PMs and predicted times change-out of limited-life items x number of scheduled change-outs. With these times a prediction of overall maintenance time per period is made. Assuming the system is shutdown during maintenance we can then predict availability. As the design matures and the Failure Mode and Effects Analysis/ Critical Items List (FMEA/CIL) and supplier maintainability program data matures, the overall availability (as well as other maintainability figures of merit) is recalculated. The data generated by the maintainability analysis serves to appraise project management of the overall maturity of the design and the design's ability to meet program objectives.

The *second phase* of maintenance is handling failures, performing preventive maintenance and replacing life-limited items. Eventually the deployed unit breaks down. The failure must be detected and isolated to the actual failed ORU/LRU. How is the failure detected, and how is the maintenance action planned and executed? Can it be combined with any other maintenance actions or preventive maintenance activities? The on-orbit or flight line maintenance is performed by

removing and replacing the failed unit. But what do we do with the broken ORU/LRU?

The *third phase* involves the handling of failed components. Here, repair level analysis evaluates the failed ORU or LRU to determine whether it should be repaired or replaced. If it is to be repaired it may be done in house (intermediate maintenance, at a maintenance depot (where more specialized equipment and better diagnostic instrumentation might be available) or at the factory. (The following section discusses the Maintenance Concept Document (MCD) in more detail). Then the unit needs to be recertified, retested, receive final checkout and be returned to the spare parts storage area (preferably bonded storage).

Only by developing the complete maintenance concept and the maintenance requirements early in the development process will the design really be impacted by maintenance needs. The operational requirements document, the mission (or "science") requirements document and the maintainability concept document with preliminary requirements should be the design drivers. Then can effective trade studies, systems analysis and functional analysis and allocation be performed. Then trade studies with reliability and maintainability alternatives can be used to evaluate total system cost. Reliability and maintainability alternatives selections will drive maintenance and repair costs, shipping costs, ORU/ LRU spare costs, long lead time components and components manufactured by complex processes.

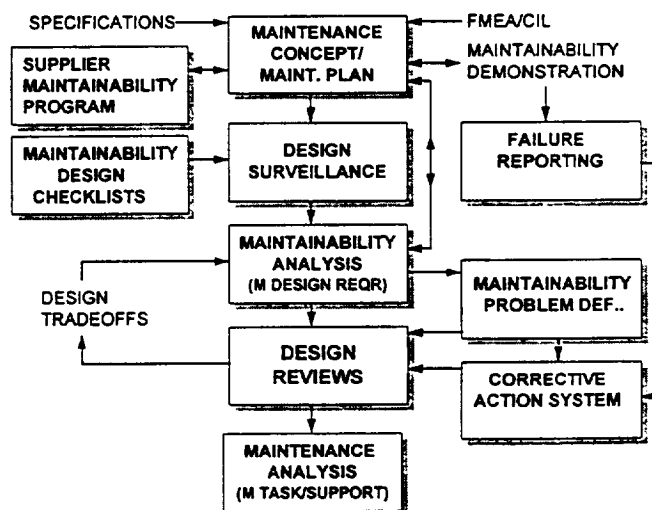


Fig. 15--Maintainability Analysis Process

*Documents:* There are a number of documents (see Fig. 16) that typically support a large scale engineering project (some describe the activities we have already discussed). They officially start with a basic plan and the Maintenance Concept Document (MCD). The MCD together with the operations concept document and the science requirements are the chief design and cost drivers for the future system. The individual documents are as follows:

1. **Maintainability Program Plan (MPP)** [required]: This document defines the overall maintainability program, activities, documents to be generated, responsibilities, interfaces with the logistics function and the general approach to analysis of maintenance.

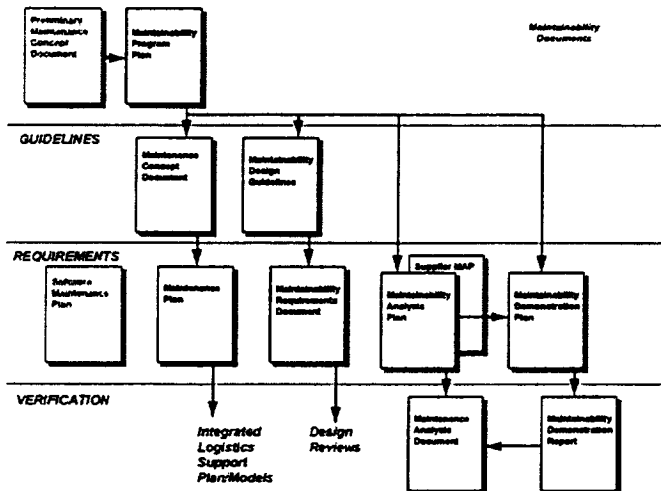
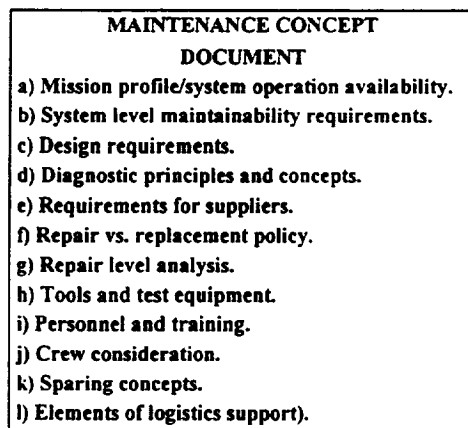


Fig.16--Maintainability Documentation

2. **Maintenance Concept Document (MCD)** [required]: This document (see Fig.17) defines the *proposed* way maintenance is to be performed on the product. The MCD details the aims of the maintenance program, support locations and a detailed description of how all maintenance activities are to be carried out (details of support and logistics may additionally be specified depending on document requirements). It also defines the input and output data requirements and how maintenance activities are to be scheduled. Various sections include:

Fig.17--MAINTENANCE CONCEPT DOCUMENT



- a) **Mission profile/system operational availability:** How often, over what period of time is the system operational? Also, what is the geographic deployment of system. Where will the systems be that need to be repaired?
- b) **System level maintainability requirements:** What are the allocated and actual reliability requirements, and maintainability requirements (MTTR MTBF, etc.)?

- c) **Design requirements:** What constitutes a maintainable element that can be removed or replaced (e.g., an Orbital Replaceable Unit (ORU) or Line Replaceable Unit (LRU)?). What are the size and weight limits?
- d) **Diagnostic principles and concepts:** How will a failure be detected and isolated? How will repairs be evaluated?
- e) **Requirements for suppliers:** What information about parts and components must the supplier give? How will the first, second and third tier suppliers support their products, how fast will they be available and how long will they be available?
- f) **Repair versus replacement policy:** How is the decision made to repair or replace a unit. If repaired how is it re qualified?
- g) **Repair level analysis:** Where will different failures be repaired? Which repairs will be made on-orbit (or on the flight-line)? Which repairs will be made at an intermediate maintenance facility (depot) and which will be made at the factory.
- h) **Tools and test equipment:** What diagnostic, alignment and check-out tools will be required for each level of maintenance (repair)?
- i) **Personnel and training:** What is the level of training required for the units at each level of maintenance (from simple remove and replace to detailed troubleshooting of an ORU/LRU)?
- j) **Crew considerations:** What time will be allocated for preventive & corrective maintenance: How much time can a flight crew, ground crew give to maintenance during or between missions?
- k) **Sparing concepts:** What spares will be onboard versus delivered when needed? Will failed units be repaired or replaced? What are the general repair policies?
- l) **Elements of logistics support (optional):** Where will all the test, ground support equipment and inventory control supplies be located?

3. **Maintenance Plan (MP)** [required]: This document defines the *actual* way maintenance is to be performed on the product. The MP gives detailed requirements for repair or replacement analysis, the location for and levels of maintenance and other detailed requirements of how the maintenance is to be carried out.
4. **Maintainability Design Guidelines (MDG)** [optional]: This guideline contains suggestions, checklists, and discussions of ways to make the design maintainable. Related safety, human factors, factors to consider for vendors and transportation issues may also be considered.
5. **Maintainability Requirements Document (MRD)** [required]: This document gives the specific requirements (criteria) to facilitate maintenance or repair actions in the predicted environment. It contains all maintainability requirements.



6. **Maintainability Analysis Plan (MAP)** [required]: The Maintainability Analysis Plan specifies in detail how the maintainability of the system is assessed. The Maintainability Analysis Plan also documents the **process** that translates system operational and support requirements into detailed quantitative and qualitative maintainability requirements with the associated hardware design criteria & support requirements and provides basic analysis information on each ORU/LRU. This document includes evaluation processes for preventive, corrective and emergency maintenance. The MAP documents the formal procedure for evaluating system and equipment design,<sup>3</sup> using prediction techniques, failure modes and effects analysis procedures and design data to evolve a comprehensive, quantitative description of maintainability design status, problem areas and corrective action requirements.
7. **Supplier Maintainability Analysis Plan**[optional]: This report outlines methodology to *evaluate suppliers* for conformance to maintainability standards.
8. **Maintenance Analysis Document** [required]: This document provides the details of how each ORU/LRU is to be maintained including detailed maintenance tasks, maintenance task requirements and maintenance support requirements.
9. **Maintainability Demonstration Plan** [optional]: This plan documents the process that translates (and verifies) system operational and support requirements into actual test plans for maintainability of systems/subsystems. The output, the Maintainability Demonstration Report includes MTTRs and maintenance descriptions.

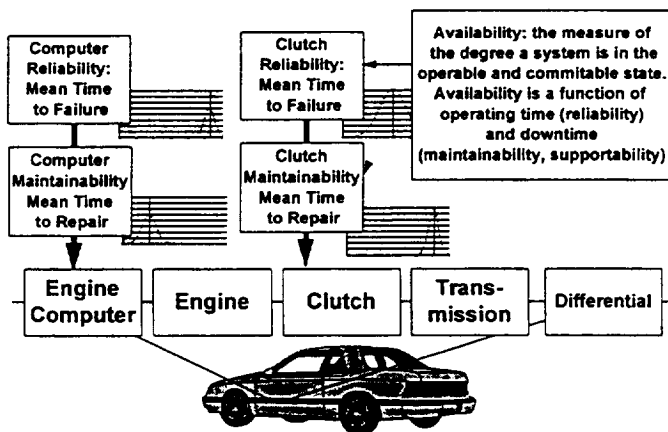


Fig.18--Factors Affecting Maintainability

<sup>3</sup> To help the reader distinguish between the various aspects of maintainability evaluation, the following is useful. There are basically three stages to the overall evaluation process, (1)Engineering Design Analysis, (2)Maintainability Analysis and (3) the Maintainability Demonstration. Engineering *DESIGN* Analysis involves the initial trade studies and evaluation to determine the optimum ORU design configuration. This also involves identifying safety hazards, reaction time constraints for critical maintenance and an evaluation of diagnostic alternatives. Maintainability *ANALYSIS* involves an expanded detailed analysis of the final design to determine all maintainability system parameters. The Maintainability Demonstration then specifies *TESTS* to verify the data collected during the maintainability analysis

## 6. MAINTAINABILITY ANALYSIS MATHEMATICS

As previously stated, the end goal of system performance is to have the system available when the system is need. As Fig.18 shows, the failure rate, the mean time to repair, the time to acquire spares as well as operational constraints all affect availability.

Availability requirements can be met with an extremely reliable system, a system that is easy to repair and has an adequate supply of spare parts, or a combination of both. System use and mission profile will also affect system availability Requirements. Fig.19 shows a number of NASA and other examples are given of continuous and intermittent mission requirements.

- **Continuous operation**
  - Space craft (LEO)
  - Space station
  - Air traffic control system
- **Intermittent operation -- on demand**
  - Emergency vehicle
  - Research fighter
  - Shipboard gatling gun
- **Intermittent operation -- scheduled**
  - Space experiment
  - CAT scan / MRI equipment in hospital
  - Space Shuttle main engines

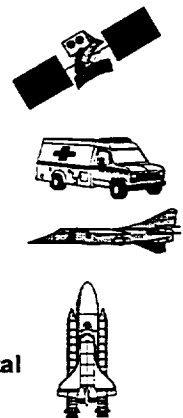


Fig.19--Mission Profile Drives Maintainability Options

Is continuous operation required? Examples a critical life-life-support system on space station or an air traffic control system If so, the reliability has to be very high and/or backup systems may be needed.

An intermittent operation requirement is a different story: If availability is on demand then the Built-In-Test/Built-In-Test-Equipment (BIT/BITE), and preventive maintenance functions have to be perfected and evaluated (through accumulating many hours on similar units). Still downtime for preventive maintenance has to be accounted for with spare systems. If there is *scheduled intermittent operation*, critical components can be replaced or continuously monitored

For our mathematical analyze that follows, we will assume we have a system that requires continuous operation except for scheduled preventive maintenance. We will assume a temporary backup system exists or that the system can be down for short periods of time. Once the system is put into operation it might experience periods when not all features are operating but the failures can be tolerated until the next scheduled preventive maintenance period (for example: failure of a monitoring sensor or a BIT/BITE function).

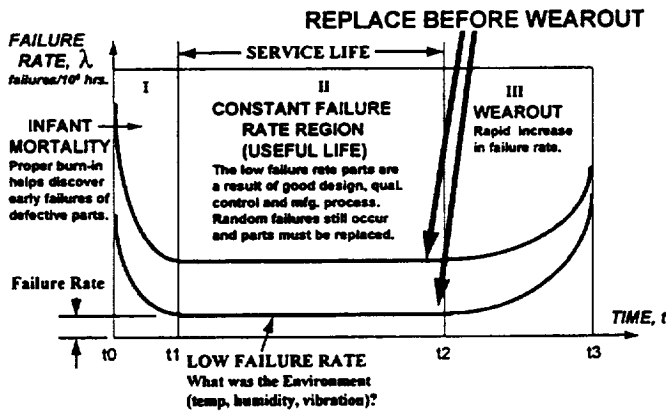


Fig.20--Maintenance of Limited-Life Items

Maintenance includes: (1) corrective maintenance: replacement of failed components or ORU and LRUs; (2) Preventive maintenance,<sup>4</sup> scheduled maintenance identified in the design phase such as lubrication, alignment, calibration or replacement of wear items such as clutches, seals or belts; (3) Replacement of life limited items as illustrated in the following Figure 20.

Distinctions have to be made between the Availability calculated from MTBF that is only valid in region II and availability once a component enters its wearout region. Here the failure rate may increase exponentially and it is more difficult to predict. The generally accepted practice is to replace life limited items before they enter their wearout period. If the mission life extends into Region III (wearout) then essentially the part is a life limited component and it will be replaced before the beginning of the wearout stage at time "t2." IF the mission life is somewhere in Region II--Constant Failure Rate Region, then the component will only be replaced if it fails randomly. No scheduled replacement time will be made.

Fig.21--MAINTAINABILITY FORMULAS

**Inherent Availability** =  $MTBF / (MTBF + MTTR)$   
**MTBF** = Mean Time Between Failures  
**MTBF** =  $1 / \lambda$  (for exponential failure rate).  
**MTTR** = Mean Time to Repair  
**T** =  $DI + DL + GA + RR + SR + CK + CU$  (total corrective maintenance time = time for diagnostics, local delivery, gain access, removal and replacement, system restoration, checkout and close up)  
**MLDT** = Mean logistics delay time  
**MADT** = Mean Administrative Delay Time

Availability can be calculated as the ratio of operating time to total time, where the denominator, total time, can be divided into operation time ("uptime") and "downtime." System availability depends on any factor that contributes to downtime. Underpinning system availability, then are the reliability and maintainability of the system design but support factors, par-

<sup>4</sup>Preventive maintenance can be aimed at software as well. Fixing corrupted tables, updating databases and loading revisions of software are also an important part of scheduled maintenance

ticularly logistics delay time can also play a critical role especially when a long supply line exists (such as with the International Space Station (ISS)). Assuming these factors stay the same, then the following availability figures of merit can be calculated.

**Inherent Availability** =  $MTBF / (MTBF + MTTR)$  This considers only maintenance of failed units.

**Achieved Availability** =  $MTTMA / (MTTMA + MMT)$  This inherent availability plus consideration for time spent for preventive maintenance and maintenance of life limited items.

**Operational Availability** =  $MTTMA / (MTTMA + MMT + MLDT + MADT)$  This is achieved availability plus consideration for all delay times as when spares or maintenance personnel are not available).

where:

**MTBF** = Mean Time Between Failures

**MTTR** = Mean Time to Repair

**MTTMA** = Mean time to a maintenance action (corrective, preventive & replacement of limited life items)

**MMT** = Mean (active) maintenance time (corrective, preventive and replacement of limited life items)

**MLDT** = Mean logistics delay time (includes downtime due to waiting time for spares or waiting for equipment or supplies). Maintenance downtime is the time spent waiting for a spare part to become available or waiting for test equipment, transportation or a facility area to perform maintenance. For this discussion it does *not* include *local* delivery such as going to a local storage location and returning to the work sight and returning the used part to a location for transport to a repair facility.

**MADT** = Mean Administrative Delay Time (includes downtime due to administrative delays, waiting for maintenance personnel, time when maintenance is delayed due to maintenance personnel being assigned elsewhere and filling out forms, signing out the part.)

**MDT** = Mean downtime (include downtime due to (active) maintenance and logistics delays)

Availability measures can also be calculated for a point in time or as an average over a period of time. Availability can also be evaluated for a degraded system. For the remainder of our discussion, we will assume average availability and maintainability factors.

Other factors of importance include: (1) maximum allowable time to restore, (2) proportions of faults and percentage of time detected as a function of failure mode, (3) maximum false alarm rate for built in test equipment and (4) maximum allowable crew time for maintenance activities.

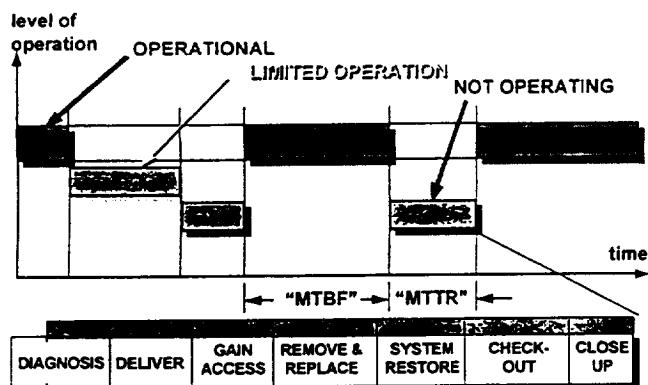


Fig. 22--Maintainability During System Operation

We also want to look in detail at an individual corrective maintenance action. There are a number of elements that make up a maintenance action and once these elements are combined other factors must be considered before the overall impact on crew hours maintenance hours and other maintenance parameters are determined. These include:

1. Maintainability prediction using the most effective methods available emphasize estimation of the time-to-restore at the ORU/LRU level. The time to restore for a failed unit is The *Total Corrective Maintenance Time*,  $T$ , (in minutes) for each ORU is:

$$T = DI + DL + GA + RR + SR + CK + CU$$

Where:

$DI$  = diagnostic time to detect and isolate a fault to the ORU level (minutes).

$DL$  = local delivery of spare ORU/LRU as opposed to shipping in from a remote location (minutes).

$GA$  = time required to gain access to the failed ORU (minutes).

$RR$  = time required to remove and replace the defective ORU (minutes).

$SR$  = time required to restore system (including alignment, etc.) (minutes).

$CK$  = time required to complete system checkout (minutes).

$CU$  = time required to close up system (minutes).

2. The Mean Time To Repair (MTTR) (hours) for the ORU (on-orbit) is as follows (It shall be assumed for this exercise that the crew size shall be one for all repair operations.):

$$MTTR_{ORU} = (T \times Z) / 60$$

Where:

$Z$  = the one-g to micro-g conversion factor

3. The Mean time to a maintenance action, MTTMA, based on a yearly average is

$$MTTMA = (MMHY_c + MMHY_p + MMHY_l) / 8640$$

4. The Maintenance Hours per Year (MMHY) for corrective (c), preventive (p) and life limited replacement (l) are as follows (note that there are approximately 8640 hours in a year):

$$MMHY_c = DC \times MTTR_{ORU} \times K \times (8640 / MTBF)$$

$$MMHY_p = MMP \times F(P)$$

$$MMHY_l = MTTR_{ORU} / T_l$$

where:

$DC$  = Duty Cycle of the ORU (percentage)

$MTBF$  = mean time between failures (hours)

$MMP$  = Mean hours to perform preventive task. (hours)

$F(P)$  = preventive task frequency per year.

$K$  = MTBF to MTBM conversion factor

$T_l$  = life limit for the ORU. (hours)

5. Maximum Corrective Maintenance time ( $M_{max}$ ) is the + 90% time for a normal distribution. It is assumed that since this is a manual operation and not a subject of wearout, that the normal distribution will apply. Then:

$$M_{max} = MTTR_{ORU} + (1.61 \times \sigma)$$

Where:

$\sigma$  = is the standard deviation of the repair time.

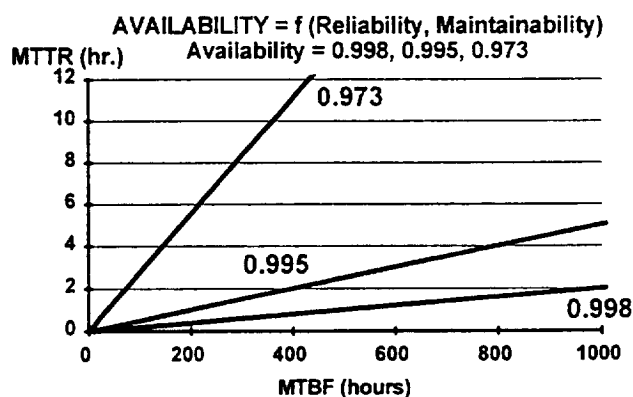


Fig. 23--The Relationship of MTTR and MTBF

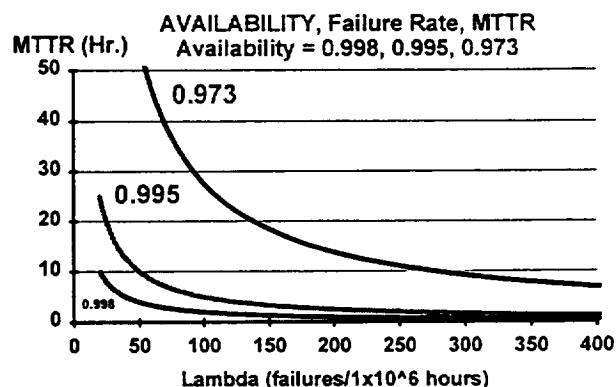


Fig. 24-- The Relationship of MTTR and Failure Rate

Plots of typical inherent availability are presented in Fig. 23 as a function of MTTR and MTBF. Here, solving the expression: Inherent Availability =  $MTBF / (MTBF + MTTR)$

for MTTR gives  $MTTR = (1 - \text{Inherent Availability}) \times MTBF$ . Fig. 24 shows MTTR as a function of failure rate (assuming an exponential rate). For an exponential distribution, the failure rate,  $\lambda = 1/(MTBF)$ . Substituting this into the above expression for inherent availability and solving for MTTR yields the results shown.

## 7. ADDITIONAL CONSIDERATIONS

As previously mentioned, to speed the system back into operation, the system is typically divided into units (ORUs/LRUs) which can easily be replaced, either on-orbit or on the flight line. This means that maintenance on-orbit (or on the flight line) will usually only replace these items. Fig. 25 and Fig. 27 shows some important questions we need to ask for our maintainability analysis.

Fig. 25—MAINTAINABILITY QUESTIONS

- How much downtime is acceptable?
- What will be replaced on the "flight line:" (what should be designated an LRU or ORU?)
- How will a failure be diagnosed and isolated to an ORU/LRU? BIT/BITE? Manual processes? Software? A combination?
- Will the failed units be scrapped or repaired?
- If repaired: for each type of failure, what should be repaired? where (depot/lab/factory)? by what skill level?

First we must know what has failed (see Fig. 26). A combination of built in testing and diagnostic procedures (with the needed tools and instruments) must be available to diagnose a fault/failure to at least the ORU/LRU level. If it cannot be determined with that fidelity, then the wrong item might be replaced.

Fig. 26—BUILT-IN-TESTS PROCEDURES

- Do you know what is going to fail?
- Maintenance records allow preventive maintenance where critical items are replaced at a known percentage of life.
  - Smart diagnostic features sense impending failures.
- Do you know what has failed?
- Does built-in-test equipment or readily available external test equipment quickly diagnose the problems.
- Do you know how you are going to handle each failure?
- Has a repair analysis been performed on all likely failures? How will each be diagnosed and repaired?
  - Has the FMEA been evaluated for failures and corrective actions?

Then the questions remains: can all plausible and probable failure modes (based on the FMEA/CIL) be diagnosed with BIT/BITE?; and can the necessary diagnostic procedures be carried out by a crew member or technician on the flight line? The answers to these questions determine the design concept for maintainability. The aim of this analysis is to reduce downtime. Other requirements include to evaluate ORUs/ LRUs as follows:

Maintainability Guidelines/Requirements for ORUs:

1. On-orbit replacements of ORUs should not require calibrations, alignments or adjustments. Replacements of like items in ORUs should be made without adjustments or alignments (this will minimize maintenance time).
2. Items that have different functional properties should be identifiable and distinguishable and should not be physically interchangeable. Provisions should be incorporated to preclude installation of the wrong (but physically similar) cards, components, cables or ORUs with different internal components or engineering, revision number, etc. Reprogramming, changing firmware and changing internal switch settings may be allowed with special procedures and safeguards.
3. All replaceable items should be designed so that it will be physically impossible to insert the incorrectly. This is a basic maintainability and safety requirement.

Additional maintainability considerations to be incorporated into the design should also be considered. Some of these are:

1. Any ORU, SRU<sup>5</sup>, their sub-components or cards that are physically identical should be interchangeable (Cables and connectors are excluded). Identical hardware (e.g. a signal conditioning card) shall not be made unique. Different software/switch settings do not affect "identity." The ability to replace ORUs, etc. with an identical unit from an inactive rack will improve availability.
2. Standardization should be incorporated to the maximum extent possible throughout the design. In the interest of developing an efficient supply support capability and in attaining the availability goals, the number of different types of spares should be held to a minimum.
3. The ORU should be designed from standard off-the-shelf components and parts.
4. The same items and/or parts should be used in similar ORUs with similar applications (e.g., boards, fasteners, switches and other human interface items, fuses, cable color designations, connectors except to avoid improper hook-ups, etc.).

Fig. 27—MAINTAINABILITY QUESTIONS continued

- What preventive maintenance needs to be performed?
- What kind of maintenance tests need to be performed?
- Can all components be inspected for structural defects?
- How will structural defects be detected and tracked?
- Have acceptable damage limits been specified?
- Are safety related components easy to replace?
- Are there safety issues that occur during maintenance?
- How is corrosion controlled?
- Are limited-life items tracked for maintenance?

<sup>5</sup>SRU stands for Shop Replaceable Unit. A part or component that is designed/designated to be replaced in a depot or at the manufacturer. For instance, it may be highly modular but its failure can not be easily detected on-orbit or on the flight line.

- Equipment control panel positions and layouts (from panel to panel) should be the same or similar when a number of panels are incorporated and provide comparable functions.

Some disciplines which relate to basic maintainability analysis will also be discussed:

Fig.28--RELATED TECHNIQUES AND DISCIPLINES

- Supportability
- Reliability centered maintenance
- Integrated logistics support
- Personnel training
- Maintainability, Quality and Reliability

*Supportability* can be thought of as the global term that covers all maintenance and logistics activities. Can the unit be supported? Yes, if it can be maintained and if spare parts can be delivered to the unit.

*Reliability Centered Maintenance (RCM)* is a maintenance process based on identification of safety critical failure modes and deterioration mechanisms through engineering analyses and experience. This allows determination of the consequences of the failure based on severity level. Then maintenance tasks can be allocated according to severity level and risk. The RCM logic process considers maintenance task relative to: (1) Hard-time replacements: Degradation because of age or usage is prevented by replacement. Maintenance is at predetermined intervals. (2) On-condition maintenance : Degradation is detected by periodic inspections. (3) Conditional maintenance: Degradation prior to failure is detected by instrumentation/ measurements.

*Integrated logistics support* includes the distribution, maintenance and support functions for systems and products. It includes (1) Maintenance, (2) Supportability, (3) Test and support equipment, (4) Personnel training, (5) Operations Facilities, (6) Data (manuals), (7) Computer resources (for maintenance of equipment and for software maintenance) and (8) Disposal. *Personnel* considerations involve analyzing what level of expertise is needed at each level of maintenance (on the flight line, in a depot (intermediate repair facility) or in the factory) to effectively perform the repairs.

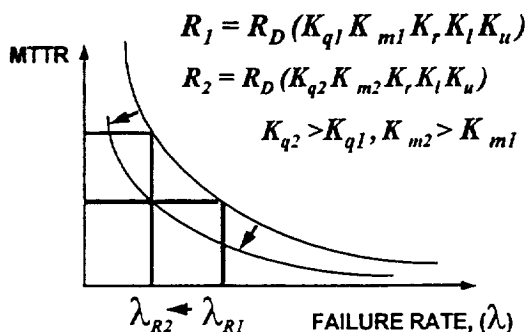


Fig.29--Quality Effect on Maintainability

*Maintainability, Quality and Reliability:* Fig.29 shows the relationship among the three? As quality and manufacturing techniques improves, reliability increases. Therefore for the same availability, MTTR may increase and a higher availability may be attained. The reliability of the product is given by  $R_{product}$  where the design stage reliability,  $R_D$ , is modified by various K factors. The K factors denote probabilities that the design-stage reliability will not be degraded by any given factor. The K factors are external contributors to product failure

$$R_{product} = R_D (K_q K_m K_r K_l K_u)$$

$K_m$  = manufacturing, fabrication, assembly techniques.

$K_q$  = quality test methods and acceptance criteria.

$K_r$  = reliability fault control activities.

$K_l$  = logistics activities.

$K_u$  = the user or customer activities.

Manufacturing processed or assembly techniques that are not in statistical control can greatly affect reliability. Special cause variation, change in raw materials or not following manufacturing procedures can dramatically reduce reliability of a product. Poor test methods may allow substandard components to be used in a product that would fail final test screenings and get into the operating population. Poor packaging, shipping practices, storage, etc. will raise the failure rate. The user or customer may abuse the product using it for things it was not intended or in a new unspecified environment. All of these problems require that our systems be maintainable when they are in the operational phase.

## 8. MAINTAINABILITY PROBLEMS

The maintainability, reliability and cost data items in Fig.30 represent the information that is required to perform a maintainability analysis. We will consider how these data items interact and how maintainability trades can be made.

ORU/LRU weight (kg)	Volume (m <sup>3</sup> )
Definition partial operation	Power reqr. (watts)
MTBF (hours)	Repair cost (\$)
Cost (\$)	Transportation (\$)
Life/wearout (hours)	Spares location(s)
MTTR (hours/repair)	Operation time (hours)
FMEA	Operation Period (hours)
Availability	BIT capabilities
Preventative maintenance	Tools required
Supportability	Manifest time (hours)

Fig.30--Maintainability Figures of Merit

First lets consider two simple examples (refer to Fig.21-- Maintainability Formulas, for the basic math involved). These are given in Fig.31 and Fig.32.

### BASIC RELIABILITY MATH

- Five pressure transducers (model c-4) were tested and they were found to fail after an average 2257 hours. Time studies have shown it takes 5.5 hours to diagnose, remove, replace and check out a unit.
- Assuming continuous use and an exponential failure rate, what is the MTBF, the failure rate, the reliability for a mission of 50 hours in length, and the availability.

$t_f$  for first failure = 2257 hr.       $t_m$  = mission time = 50 hr.  
MTTR = 5.5 hr.      MTBF = 2257 hr.

$\lambda = \lambda = \text{failure rate (failure/hr or failures/10}^6 \text{ hr.)}$   
 $\lambda = 1/\text{MTBF} = 1 / 2257$   
 $\lambda = 0.000443 \text{ failures / hr. or } 443 \text{ failures / } 10^6 \text{ hr.}$

Reliability =  $\exp(-\lambda t_m) = \exp(-0.000443 \times 50) = 0.9780$   
Availability =  $\text{MTBF} / (\text{MTBF} + \text{MTTR})$   
Availability =  $2257 / (2257 + 5.5) = 0.9976$

Fig.31--Reliability-Availability-Maintainability: Example 1

### BASIC RELIABILITY MATH

- Five RTD temperature sensors, (model RTD-A-7) were tested and they were found to fail after an average 4026 hours. Time studies have shown it takes 52 hours to diagnose, remove, order, receive, replace and check out a unit.
- Assuming continuous use and an exponential failure rate, what is the MTBF, the failure rate, the reliability for a mission of 50 hours in length, and the availability.

MTBF = 4026 hr.      MTTR = 52 hr.

$\lambda = 1/\text{MTBF} = 1 / 4026 = 0.000248 \text{ failures/hr.}$   
Reliability =  $\exp(-\lambda t) = \exp(-0.000248 \times 50) = 0.9876$   
Availability =  $\text{MTBF} / (\text{MTBF} + \text{MTTR})$   
Availability =  $4026 / (4026 + 52) = 0.9872$

Fig.32--Reliability-Availability-Maintainability: Example 2

One way to evaluate trade-offs is by first evaluating conformance to minimum maintainability requirements and then calculating effects of alternatives on costs (see Fig.33). To do this the following steps are needed: (1) Determine screens, minimum or maximum acceptable values for a system or component; (2) Determine which tradeoffs meet these screens; (3) Of the systems that pass, calculate costs (cost of spare, cost to ship spare, cost to install spare) (4) Determine the lowest cost system and (5) Examine the results for reasonableness.

### Fig.33--A PROBLEM SOLVING STRATEGY

- I. Determine maintainability screens.
  - MTTR maximum
  - MTBF minimum
  - Availability minimum
  - Logistics Delay Time (LDT) maximum
  - Administrative Delay Time (ADT) maximum
  - Maximum Maintenance Resource Avail.
- Screen for acceptable (passing) units.
- Pick the lowest cost unit (from those that passed).
- Evaluate results for reasonableness.

Example 3 starting in Fig.33 give a more detailed analysis of how tradeoffs (at the board or component level) involving maintenance and reliability may be made. This is a more complex problem where we want to determine the lowest cost solution to a maintainability problem with fixed requirements by following the above procedures.

First we need to determine the reliability and maintainability screening requirements. Here there is a maximum MTTR<sup>6</sup> due to maintenance crew availability, a minimum MTBF due to mission restrictions and a specified availability requirement needed to complete the mission. The operation of the system is intermittent. A detailed list of these requirements and costs is given in Fig.34.

Fig.34--SYSTEM/MISSION REQUIREMENTS & COSTS

<b>System Parameters</b>	
0.99	=(#1) AVAILABILITY MINIMUM
4.0	=(#2) MTTR MAXIMUM (Hr.)
300	=(#3) MTBF MINIMUM (Hr.)
0.3	=(#4) LDT + ADT MAXIMUM (Hr.)
<b>Mission Parameters</b>	
520	=(#5) TOTAL MISSION TIME (WEEKS)
4	=(#6) SYSTEM OPERATING TIME PER WK. (Hr.)
0.1	=(#7) MAX. RESOURCE ALLOCATION MAINT (Hr./Wk.)
6	=(#8) OPERATIONAL REQUIREMENT/ WEEK (Hr./Wk.)
87360	=(#9) TOT. MISSION TIME (Hr.)
2080.0	=(#10) TOT. SYS. OPERATING HOURS/YEAR (Hr./Yr)
<b>Cost Parameters</b>	
\$7,000	=(#11) COST OF BOARD REPAIR (\$)
\$4,500	=(#12) TRANSPORTATION COST OF BOARD (\$)
\$500	=(#13) MAINTENANCE COST ON-ORBIT (\$/Hr.)

Fig.34 gives quantitative system data that is needed to evaluate the model. This is broken down into system and mission requirements and cost restraints.

#### System Parameters

- (1) *Availability Minimum*: Based on the MTTR and MTBF for each unit, is the availability greater than or equal to the requirement (0.990)?
- (2) *MTTR Maximum (Hr.)*: What is the maximum possible repair time that can to be allowed? How long can the system be down?
- (3) *MTBF Minimum (Hr.)*: What is the minimum reliability goal of the system.
- (4) *LDT + ADT Maximum (Hr.)*: What is the maximum Logistics Delay Time allowable? For a single repair action how long does it take to deliver a replacement part from the warehouse or factory (for the total mission, turn around time for repair of boards also needs to be considered.)? Also, what is the Administrative Delay Time? How long will it take to process an order for spares and how long will it take to do other paperwork. ADT may not affect system availability but will affect total crew maintenance time used to repair the system.

#### Mission Parameters

- (5) *Total Mission Time (Weeks)*: What is the total time that the unit will be in the system and available for operation?

<sup>6</sup>Strictly speaking we do not have a "maximum MTTR" since MTTR and also MTBF do not have distributions but are derived from a distribution. This notation is kept since we are looking at a number of MTTRs etc. for various alternative boards, etc.

- (6) *System Operating Time Per Wk. (Hr.)*: How many hours per week does the unit operate and in what modes (operational, standby, etc.)?
- (7) *Max. Resource Allocation Maint (Hr/Wk)*: Are crews available for maintenance and operation of the unit? Is the MTTR reasonable so that the crew will have time to do maintenance.
- (8) *Operational Requirement/ Week (Hr/Wk)*: Are there limits on how long an item can take to be repaired? Often if a system is difficult to repair it may be "neglected" in favor of more easily maintained systems.
- (9) *Tot. Mission Time (Hours)*: What are the total clock hours that the mission is to last (irrespective of whether or not the system or board being considered is operating)?
- (10) *Tot. Sys. Operating Hours Per Year (Hr/Yr)*: What are the total hours per year the system or board being considered is operating? This is equal to (6) System Operating Time Per Week \* 52.

#### Cost Parameters

- (11) *Cost Of Board Repair (\$)*: What is the cost to repair a failed board?
- (12) *Transportation Cost Of Board (\$)*: What is the cost to transport a spare board to the site of field repairs. If it is a remote site, or on-orbit, the cost may be considerable.
- (13) *Maintenance Cost On-Orbit (\$/Hr)*: What are the allocated costs for crew maintenance time on-site or on-orbit. The cost of crew maintenance time may be considerable and significantly affect the overall trade study costs.

The above availability, maintainability and reliability screens can also be portrayed graphically as shown in Fig.35--Availability =  $f(\text{MTBF}, \text{MTTR})$ . The "solution space" described by the system and mission requirements is bounded by the 0.990 availability line, the MTBF minimum of 300 hours and the MTTR maximum of five hours. Note also that in this graph the constant availability lines are generated with MTBFs and MTTRs that represent average values. MTTR and MTBF are usually considered distributed variables with a exponential or normal distribution.

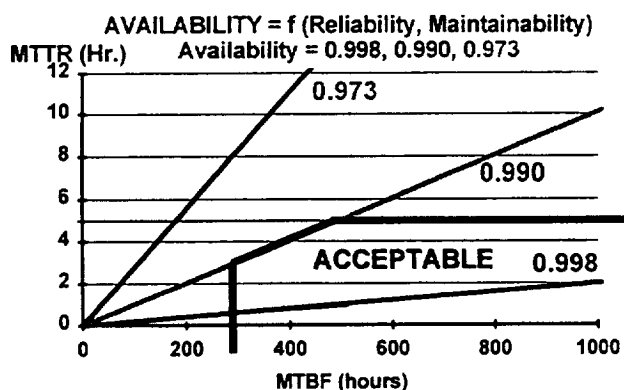


Fig.35--Problem Solution Area on an Availability Plot

Having considered the basic requirements imposed on the system and the costs associated with a maintenance action we will now evaluate individual boards which are being considered for a "black box" in the system.

Before continuing some additional assumptions need to be made. These are: (1) Only one spare board is required and it is readily accessible on-orbit or on the flight-line; (2) All

spares cost the same; (3) There are no finance (carrying) cost. (4) Repair costs for each alternative board is the same.<sup>7</sup>

Fig.36--BOARD TRADE-OFF OPTION DATA

Board Option	MTBF	Cost	MTTR	LDT + ADT
	(HR)	(\$)	(HR)	(HR)
A	B	C	D	E
2	195	74,100	3.7	0.3
2a	662	182,900	3.8	0.3
3	191	77,600	3.5	0.3
3a	583	130,800	3.7	0.3
4	199	76,600	3.3	0.3
4a	828	188,257	6.8	0.3
5	62	45,400	3.4	0.3

Second, determine which tradeoffs meet these screens. Data needed to evaluate each potential electronic board for a particular function in the system is now given in Fig.36--Board Trade-Off Option Data. Board option 1 has already been discarded for failing to meet functional design parameters. Each remaining board (with type designated in column A), has been evaluated for (B) expected MTBF or reliability (with a parts count according to MIL-HDBK-217x or possibly via testing), (C) estimated cost to purchase the board, (D) estimated time to repair the board (based on ease of diagnosis, built-in-test circuitry or software, etc.), and (E) estimated LDT (based on the supplier turn-around history) and ADT).

Fig.37--MAINTAINABILITY FIGURES OF MERIT

Board Option	Number Maint. Actions	Availability	Total Maint. Time	Total Maint. Time/Wk
	(COUNT)	(%)	(HR)	(HR/WK)
A	$F = (\#5) * (\#6) / B$	$G = B / (B + D)$	$H = F * (D + E)$	$I = H / (\#5)$
2	10.7	0.980	42.7	0.08
2a	3.1	0.994	12.9	0.02
3	10.9	0.980	41.4	0.08
3a	3.6	0.993	14.3	0.03
4	10.5	0.982	37.6	0.07
4a	2.5	0.992	17.8	0.03
5	33.3	0.944	123.3	0.24

The next step is to calculate the data required in Fig.37--Maintainability Figures Of Merit. To see if the maintainability and reliability requirements are met. The following data is calculated:

- (F) Number of maintenance actions per mission = (Total mission time per week \* ) / (MTBF).<sup>8</sup>
- (G) Availability =  $\text{MTBF} / (\text{MTBF} + \text{MTTR})$ .
- (H) Total maintenance time (hours) = number of maintenance actions per mission \* (MTTR + LDT + ADT).
- (I) Total maintenance time (hours/week) = Total maintenance time (hours) / total mission time (weeks).

<sup>7</sup> A problem arises when the boards are stored on the ground or in a warehouse (for LRUs) when there are long logistic delay times. If systems were in remote sites or on-orbit (with no local storage of spares) with only three or four deliveries of spares per year (as with the Space Shuttle) there might be considerable periods of downtime.

<sup>8</sup> The formula for column F is  $F = (\#5) * (\#6) / B$  where (#5) refers to item #5 Total Mission Time in Weeks in Fig.34 -- System/ Mission Requirements & Costs, (#6) refers to item #6, System Operating Hours Per Week and B refers to column B, MTBF in Fig.36 -- Board Trade-Off Option Data.

Note: The maintainability screens are independent and may not necessarily relate to this formula (e.g., irrespective of the required availability and minimum MTBF there may be a maximum maintenance time allowed).

Evaluating the results we find that option 2, 3, 4 and 5 fail the minimum MTBF and Availability screens. Option 4a fails the maximum MTTR screen. Options 2a and 4a that remain will be evaluated to determine which has the lowest cost.

*Third, of the systems that pass, calculate costs* (cost of repairing the failed unit, cost to ship the spare, cost to install spare, and the cost of the spare itself as well as the cost of the board itself). These figures are shown in Fig.38--Cost Calculations for the Total Mission:

(J) The Total Mission Board *Repair* Cost is equal to the cost to repair each board (at a depot or at the factory) times the total number of maintenance actions. The cost of the board repair is

Fig.38--**COST CALCULATIONS for the TOTAL MISSION**

Opt.	Tot. Mis- sion Board Repair Costs	Tot. Mis- sion Board Ship Costs	Tot. Mission Board Maint. Cost	Tot. Mis- sion Re- pair Cost	Tot. Mis- sion Board Cost Board & Spare)
	(\$ per MISSION)	(\$ per MISSION)	(\$ per MISSION)	(\$)	(\$)
A	$J=(\#11)*F$	$K=(\#12)*F$	$L=(\#13)*H$	$M=J+K+L$	$N=2*C+M$
2	\$74,683	\$48,011	\$1,861	\$124,554	\$272,754
2a	\$22,005	\$14,146	\$1,903	\$38,055	\$403,855
3	\$76,216	\$48,996	\$1,761	\$126,974	\$282,174
3a	\$24,965	\$16,049	\$1,854	\$42,867	\$304,467
4	\$73,151	\$47,026	\$1,660	\$121,837	\$275,037
4a	\$17,578	\$11,300	\$3,403	\$32,280	\$408,794
5	\$233,206	\$149,918	\$1,733	\$384,857	\$475,657

\$7,000/repair. This theoretically would be reduced by the number of spares purchased. The repair cost as well as the turn around time should be a part of the suppliers bid for the board.

(K) The Total Mission Board *Shipping* Cost is simply the cost of transportation of the board times the total number of maintenance actions. The cost of shipping the board is \$4500/shipment.

(L) The Total Mission Board *Maintenance* Cost reflects costs to change-out the board on-orbit or on the flight line. The cost to replace the board (on-orbit or on the flight line) is \$500/hr. This is assuming the board is also an ORU or LRU. It is equal to the total number of maintenance actions times the (MTTR + LDT + ADT).

(M) The Total Mission Board *Repair* Cost is simply the total of the repair, shipping and maintenance costs.

(N) The Total Mission Board *Cost* is the total mission board repair cost plus the cost of the board and the cost of one spare board. The cost of the manufacturing the board has already been given in Fig.36, column C. For this example we will assume that we need to purchase one board and one spare board.<sup>9</sup>

<sup>9</sup>Consideration also needs to be given for the quantity of spares needed to have a replacement board available at all times. This is a function of the desired probability of an available spare, the time to ship the board out for repairs, repair the board, recertify it and return it to a storage location. The detailed discussion of the mathematics of this evaluation is beyond the scope of this paper. Additional costs will also be incurred with parts storage,

*Fourth, determine the lowest cost system.* The solution is to pick the board with the lowest cost that passed the screens. Options 2, 3, 4, 4a & 5 have already failed screens. Of the two remaining candidates, 2a and 3a, 3a has the lowest cost.

*Fifth, examine the results for reasonableness.* As always, factors other than costs must be included in the analysis. Human factors, hierarchy of repairs, ease of diagnosis of problems, ability to isolate faults, ability to test the unit, manufacturer's process controls and experience and the ability of the manufacturer to provide long term support to the unit are some of these additional considerations.

## 9. CONCLUSION

Fig.40--**MAINTAINABILITY PROGRAM BENEFITS**

- Makes a system readiness/availability
- Provides conditions for the true value of reliability tradeoffs.
- Provides for an accurate maintainability and logistics program cost assessment.
- Provides for system growth.
- Reduces maintenance manpower.
- Reduces operational costs.
- Reduces total cost of ownership.

The benefit of a system maintainability program is mission success which is the goal of every NASA System Reliability and Quality Assurance (SR&QA) office.<sup>10,11</sup> A well planned maintainability program gives higher availability at lower costs. A design with easily maintained (and assembled) modules results. Considering maintenance prevents the inclination to use lower cost components at the expense of reliability unless maintainability tradeoffs justify them. Finally, maintainability analysis forces considerations of potential obsolescence and the need for upgrades<sup>12</sup> as well as reducing overall maintenance hours and the total cost of ownership.

inventory management, loss and damage in storage, and carrying costs for the spare parts.

<sup>10</sup>NASA Lewis Research Center (LeRC) is designing a 2nd generation instrument to measure microgravity on the space station. The operating time for the instrument is expected to be 10 years. Reliability analysis has shown "low" reliability for this mission even if we can get all of the components to have an MTBF of 40,000 hours. Therefore we are developing a maintenance program with an on-orbit repair time of 700 hours. This should give us a suitable availability for the mission.

<sup>11</sup> NASA LeRC had an interesting experience on one of our space instruments. The instrument was designed for a mission time of 18 hours with a reliability greater than 0.90. It was suggested that we use the instrument on MIR for a 3,000 hour mission. The reliability "fell" to 0.40 when this and other factors were considered. Maintainability was factored in with selected spare parts, software was added to perform Built-In-Test of the unit (BIT). The mission specialists were also trained to do repair work. The availability was returned to its previously acceptable level (with the previous level of reliability). The instrument has successfully collected data on MIR.

<sup>12</sup>For example, a ruggedized optical disk drive required maintenance after each flight on the Shuttle or after 450 hours of operation. This was a process that took four weeks. This was unacceptable to NASA when the system was to be placed on MIR (the Russian Space Station). To correct the problem, the drives were replaced with another component that greatly reduced maintenance time.





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